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Economic feasibility of development of wind power plants in coastal locations of Saudi Arabia – A review

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ABSTRACT

Climate change and depletion of natural resources are serious issues that have potential impact on the economic and social development of countries. In this perspective, the governments world-wide are mobilizing initiatives to exploit renewable energy sources to mitigate increasing demand of energy, volatile fuel prices, and environmental concerns. Renewable energy (wind/solar) based power system is a nature-friendly option for power production to foster sustainable development challenges. In the present study, the economic feasibility of development of 75 MW wind power plants (wind farms) in the coastal locations of the Kingdom of Saudi Arabia (K.S.A.) has been studied/reviewed by analyzing long-term wind speed data. Attention has been focused on four coastal locations (Al-Wajh, Jeddah, Yanbu and Jizan) covering the west coast. In general, long-term data indicates that the yearly average wind speed of K.S.A. varies from 3.0 to 4.5 m/s at 10 m height. The wind farms simulated consist of different combinations of 600 kW commercial wind machines (50 m hub-height). NREL's (HOMER Energy's) HOMER software has been employed to perform the techno-economic assessment.

The study presents monthly variations of wind speed, cumulative frequency distribution (CFD) profiles of wind speed, monthly and yearly amount of energy generated from the 75 MW wind farms (50 m hub-height) at different coastal locations of K.S.A., cost of generating energy (COE, $/kWh), capacity factor (%), etc. The CFD indicates that the wind speeds are less than 3 m/s for 45%, 53%, 41%, and 52% of the time during the year at Al-Wajh, Jeddah, Yanbu and Jizan respectively. This implies that wind electric conversion systems (WECS) will not produce energy for about 41–53% of the time during the year. The annual energy produced by 75 MW wind farms (50 m hub-height) has been found to be 107,196, 81,648, 135,822, and 80,896 MWh at Al-Wajh, Jeddah, Yanbu and Jizan respectively. The cost of wind-based electricity by using 600 kW (50 m hub-height) commercial WECS has been found to be 0.0536, 0.0704, 0.0423, and 0.0711 US$/kWh for Al-Wajh, Jeddah, Yanbu and Jizan respectively. Also, attempt has been made to determine the capacity factor (CF) of wind-based power plants, the CF has been found to vary from 12% to 21% for different locations of the Kingdom.

Contents

1. Introduction

Renewable energy provides an opportunity to promote sustainable development in those regions where good renewable

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wind/solar resources are available and hence reduce dependence on fossil fuel-based energy. Other driving forces for utilization of renewable energy sources include vast growth in demand for electricity, increasing magnitude of carbon emissions due to burning of fossil fuels, maturing of technology, etc. More importantly, renewable energy (wind or solar) is considered as a step towards a healthy global environment. It lifts the living standards to the levels of the industrialized countries. Wind is developing into a alternative power source in several countries, and is playing a appreciable role in meeting the energy challenges that the world is facing today. Literature reports that wind energy (being freely accessible, in-exhaustible, site-dependent, environment-friendly, non-polluting) is being vigorously pursued by a number of developed and developing countries with average wind speeds in the range of 4–10 m/s, in an effort to reduce their dependence on fossil-based non-renewable fuels [1–7]. Cumulative global wind energy capacity reached about 159,213 MW as of 2009. Currently, the price of generating energy using commercial WECS is in the range of 4–5 cents per kWh. The technology of the wind machines has improved remarkably over the last 5 years. WECS in the range of 3.2 MW are commercially available. The above factors have stimulated the rate of increase in installed capacity during the last 10 years and is in the range of 25–30% per annum [8]. Typical wind power applications include (but not limited to) lighting, military installations, communication/gas stations, electricity for remote settlements (which are far from utility grid), water pumping for irrigation, cathodic protection of oil pipe lines, etc.

Stand-alone WECS or wind farms require large storage capacity (to meet the load demand) because of their intermittent nature (i.e. wind resources are seldom consistent). Energy storage provides the ability to store power generated by wind farms at times of low demand and release that energy at times of high demand (contribute in electrical peak load shaving). The strengths and weaknesses of wind farms are highlighted in Ref. [7]. More often, wind farms are deployed in grid-connected mode (grid-friendly). Many countries are harnessing wind resource with different scales ranging from demonstration projects to commercial size wind farms. Literature clearly highlights that efforts are being made world-wide in development and establishment of wind farms [9–21].

The electrical power demand in Saudi Arabia is increasing at an alarming rate. This demand is driven by rapid population growth coupled with a large number of mega industrial projects. The installed generating capacity of the power plants reached 45,000 MW and with a peak load of 41,000 MW in 2009 [22]. The demand for electricity is expected to reach about 55,000 MW by 2020. In general, the above significant increases can be attributed to rapid growth in residential, commercial, and industrial sectors. Since, Saudi Arabia's has reasonable wind regime, an appreciable fraction of its energy needs may be harnessed from wind energy. Also, use of alternative sources of energy reduces CO_2 emission which is the principal cause of global warming. Utilization of renewable energy avoids tons of CO_2 and other pollutants which are emitted by burning oil [12]. Literature indicates that addition of 1.5 MW WECS, capable of producing about 4 million kWh of energy/year, would eliminate 5.6 million tons of CO_2 [23,24]. Utilization of renewable sources of energy is a step forward to overcome the problems of global warming and environmental degradation.

Research work related to renewable energy in Saudi Arabia has been subject matter of several earlier studies [25–29]. In the present study, long-term wind speed data (of the period 1970–1982) of four coastal locations of K.S.A. has been analyzed to assess the techno-economic feasibility of development of wind power plants (wind farms) in west coast of K.S.A. The locations considered in the study include Al-Wajh, Jeddah, Yanbu and Jizan (situated in the west coast). In general, long-term data indicates that the yearly average wind speeds of K.S.A. vary from 3.0 to 4.5 m/s at 10 m height. Attention has been focused on the feasibility of development of 75 MW wind farms/parks. The wind farms simulated consist of different combinations of 600 kW (50 m hub-height) commercial wind machines. National Renewable Energy Laboratory's (NREL's) and HOMER Energy's HOMER (Hybrid Optimization Model for Electric Renewables) software has been utilized to carry out the techno-economic analysis of wind farms. HOMER is a sophisticated/recognized tool or computer model that facilitates design of renewable wind/solar power systems. Therefore, the output of HOMER contributes for reliability of energy yield of wind farms [30]. The study presents the monthly variations of wind speed, frequency distribution/profiles of wind speed (i.e. availability of wind in different wind speed bins), etc. Emphasis has been placed on estimation of monthly and yearly amount of energy that can be generated from the proposed 75 MW wind farms (50 m hub-height) at various locations considered in the study. Attention has also been focused on diurnal power. Furthermore, the study estimates the cost of wind-based electricity (COE, US$/kWh) and capacity factor of wind power plants for different locations by using 600 kW (50 m hub-height) commercial WECS. The study deals with important issues including monthly variations of wind speed, cumulative frequency distribution (CFD) profiles of wind speed, monthly and yearly amount of energy generated from the 75 MW wind farms, cost of generating energy (COE, $/kWh), capacity factor (%), etc. CFD is a tool or frame of reference to assess the potentiality/reliability of a site

2. Background information

The Kingdom of Saudi Arabia is basically an arid/desert land with long hot summers, and short cold winters. The topographic features of the Kingdom are characterized by mountains in the west bordering the Red Sea that act as wind deflectors, large desert areas in the interior where high temperatures create low pressure cells, and the Arabian Gulf and Red sea which are sea areas in the east and west, respectively. To the west of K.S.A., the Gulf of Aqaba and the Red Sea form a coastal border of almost 1800 km. The K.S.A. is located within the latitudes 16° N and 32° N. The month of March marks the beginning of spring and the transition from winter to summer climate. Climatic conditions dictate the availability of wind energy at a site. Wind farms or WECS are characterized by availability of wind speed resource. The long-term wind speed data of different locations used in the present study covers the period 1970–1982. The information of the locations is furnished in Table 1 [31].

Saudi Arabia has approximately one-fifth of the world's oil reserves, and is the largest oil producer and exporter of total petroleum liquids in the world. Natural gas and oil had 44% and 56% share in conventional power generation in 2008. Fig. 1 shows the contribution of different energy sources in the total conventional power generation in the country [32].

Table 1
Information of selected locations.

Site/location/region	Latitude (degree N)	Longitude (degree E)	Altitude (m)
Al-Wajh (Western coast)	26° 14′	36° 26′	22
Jeddah (Western coast)	21° 30′	39° 12′	17
Yanbu (Western coast)	24° 07′	38° 03′	6
Jizan (Western coast)	16° 52′	42° 35′	5

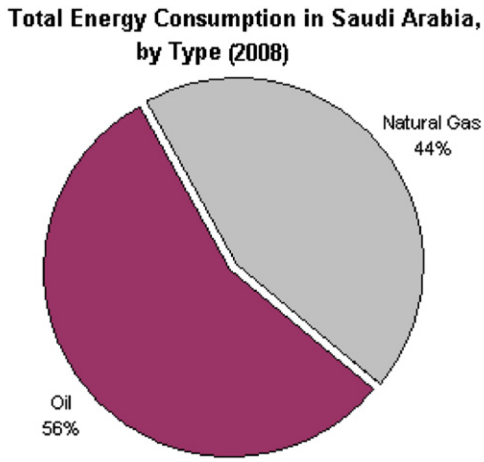

Fig. 1. Conventional power generation sources in Saudi Arabia.

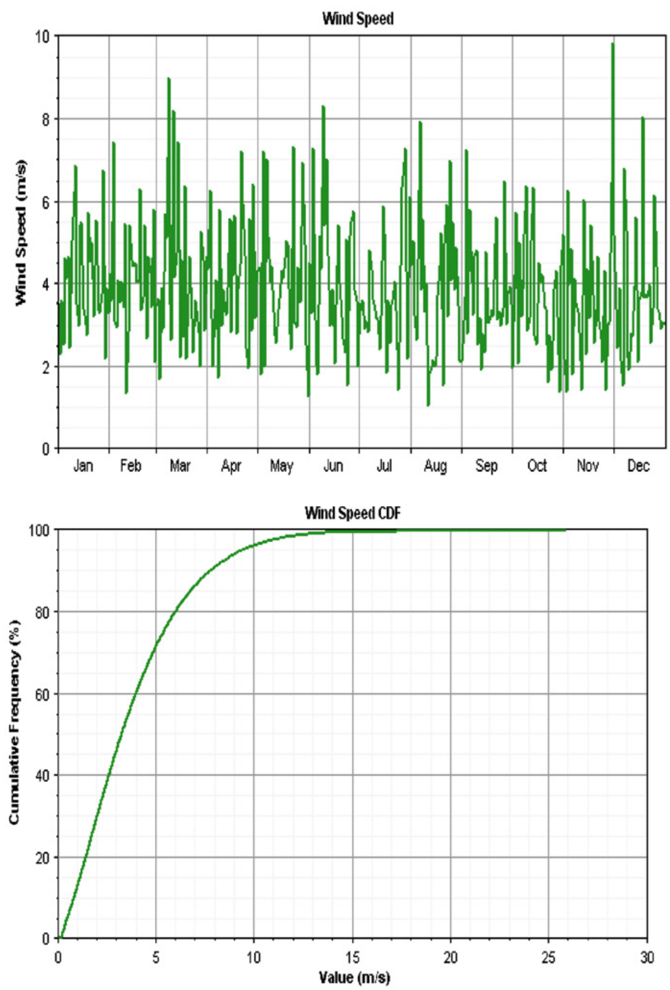

Fig. 2. Daily wind speed data and frequency distribution of Al-Wajh (West coast).

3. Wind speed data analysis and frequency distribution profiles

The long-term (1970–1982) daily average wind speeds of different locations are demonstrated in Figs. 2–5. In general, the monthly average wind speed (of the locations considered) ranges from 3.0 to 4.5 m/s at 10 m height [31]. It can be depicted from Figs. 2–5 that wind speed is relatively higher during the summer

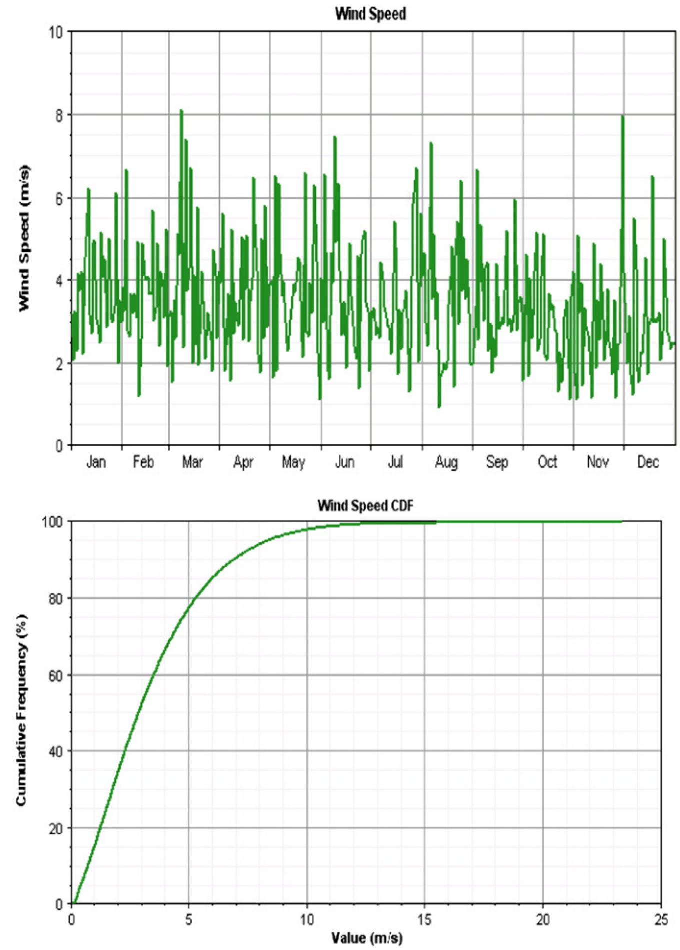

Fig. 3. Daily wind speed data and frequency distribution of Jeddah (West coast).

months (May to August) as compared to other months (*this is due to topography, this is a welcome characteristic because the load is high in summer in this part of the world*). This implies that WECS or wind farms (if installed) would produce more energy during summer time. The data also indicates that there is noticeable variation in wind speed. These variations indicate that the energy output from WECS or wind farms would be subjected to considerable differences. Also, wind is faster, less turbulent and yields more energy at 30 m or more heights above the ground (therefore wind turbines are mounted tall towers). The analysis also indicates that wind speeds are relatively stronger at Yanbu than other locations.

The cumulative frequency distribution (CFD) of wind speed of different locations is illustrated Figs. 2–5. The CFD (i.e. availability of wind in different wind speed bins) is considered as a tool to assess the potentiality of a given site. The calculations of wind energy (in HOMER) are made by matching the power-wind speed characteristics of commercial wind machines (CWMs) with the long-term hub-height wind speed data. The characteristics of the 600 kW CWMs (and other study assumptions for simulations) including operation and maintenance cost (about 3% of the initial system cost) are furnished in Table 2. The power-curve of the 600 kW wind machine is shown in Fig. 6. Today's best wind machines can achieve an overall efficiency of about 35% [33,34]. It may be mentioned that further technological milestones may change the scenario. However, many nations (in additions to those mentioned above) are putting efforts in development of wind farms [35–39]

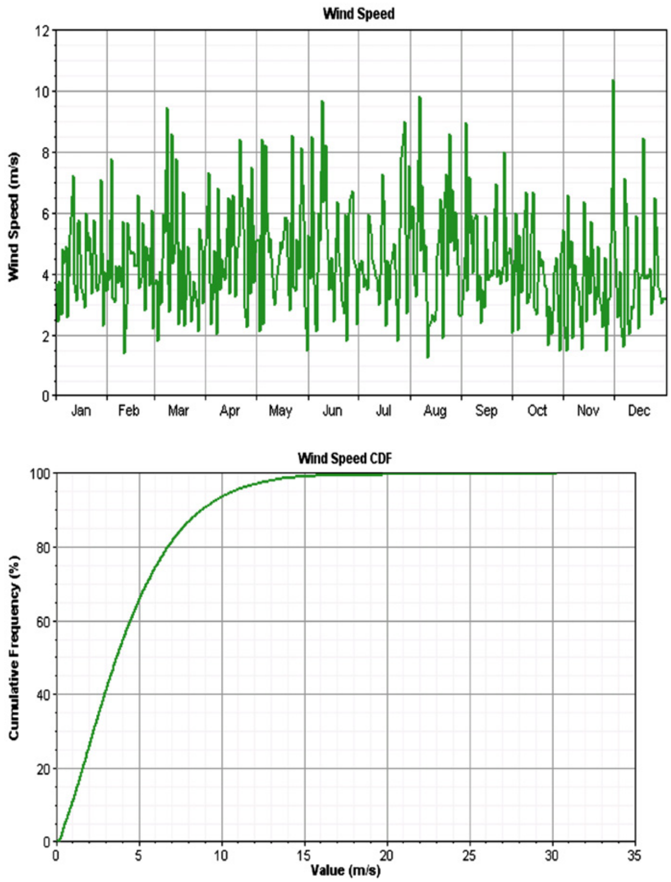

Fig. 4. Daily wind speed data and frequency distribution of Yanbu (West coast).

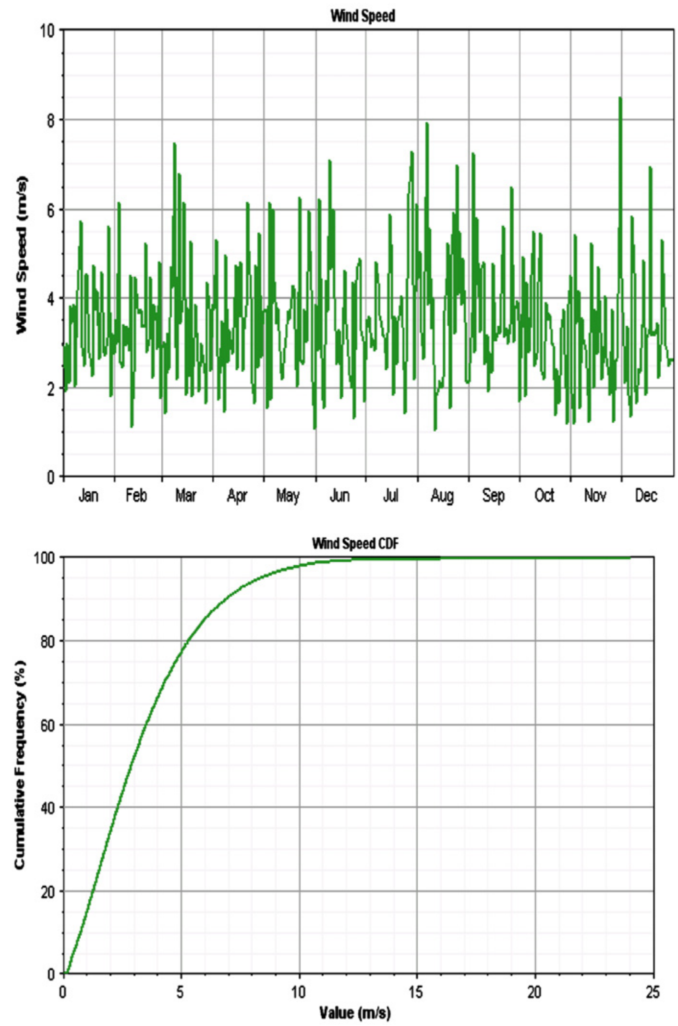

Fig. 5. Daily wind speed data and frequency distribution of Jizan (West coast).

In general, the cut-in wind speed (speed at which wind machine starts producing useable energy) of most of the CWMs is in the range of 3–4 m/s [25]. The CFD indicates that the wind speeds are less than 3 m/s for 45%, 53%, 41%, and 52% of the time during the year (as shown in Figs. 2–5) at Al-Wajh, Jeddah, Yanbu and Jizan respectively. This implies that wind electric conversion systems (WECS) will not produce energy for about 41–53% of the time during the year and hence cannot meet load demand on a continuous basis. It can also be noticed that frequency distribution of wind speeds of Al-Wajh and Yanbu are less than 3 m/s for 41–45% of the time and these are relatively better candidates for installation of WECS as compared to other locations.

4. Results and discussions

The techno-economic feasibility of development of wind power plants (wind farms) has been carried out (by analyzing long-term wind speed data) for four geographically distinct sites representing coastal locations of the Kingdom. The key parameters for assessing the feasibility of a given site for development of wind farm include average wind speed, frequency distribution of wind speed, monthly wind energy generation, yearly wind energy generation, cost of energy (COE, \$/kWh), capacity factor (%) etc. The energy generation, cost of energy, and capacity factor issues are discussed in the following sub-sections.

4.1. Energy generation from wind farms

In the present study, the selection of commercial wind machines, sizing of wind farms and energy simulations have been done using NREL's (HOMER Energy's) HOMER software. HOMER is a system design software that facilitates design of electric power systems. Input information to be provided to HOMER includes renewable resources data (e.g. wind speed data), component technical details/costs, etc. HOMER is an simplified optimization model which performs hundreds or thousands of hourly simulations over and over in order to design the optimum systems. It uses life cycle cost to rank order these systems [30].

Fig. 7 shows the monthly wind energy generation/yield from 75 MW wind farms (cluster of 600 kW wind machines, 50 m hub-height) at all the four selected sites. It can be noticed that the power generated at Al-Wajh and Yanbu sites during summer months (March to July) is greater as compared to other months. This is a favorable characteristic because the load is high during summer months in this part of the world. The energy generated at Jeddah and Jizan sites is less as compared to other locations. This indicates that Yanbu and Al-Wajh are relatively better candidates for installation of WECSs or wind farms as compared to other locations.

The annual wind energy generated from 75 MW wind farms (cluster of 600 kW wind machines, 50 m hub-height) at all the four selected sites is demonstrated in Fig. 8. It can be observed that annual wind energy yield at Al-Wajh and Yanbu sites is relatively more as compared to Jeddah and Jizan sites. The annual energy produced by 75 MW wind farms (50 m hub-height) has

Table 2
Power-wind characteristics and details of 600 kW commercial wind machine.

Wind machine model	Rated power (Kw) Rp	Rated speed (m/s) Vs	Cut-in speed (m/s) Vci	Cut-out speed (m/s) Vco	Rotor diameter (m)	Hub heights (m)	Capital cost (US$)	O & M cost (US$/year)	Turbine life time (years)
NORDEX 600	600	13.0	3	25	43	40, 50, 60	575,000	13,000	20

Rp is the maximum power obtained from the WECS, Vci is the speed at which WECS starts producing energy, Vs is the speed at which generated power reaches Rp, Vco is the speed at which WECS no longer produces power.

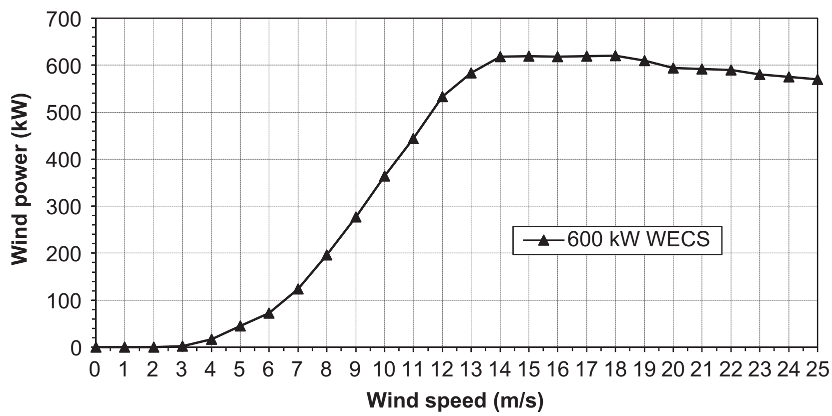

Fig. 6. Power curve of commercial 600 kW wind machine.

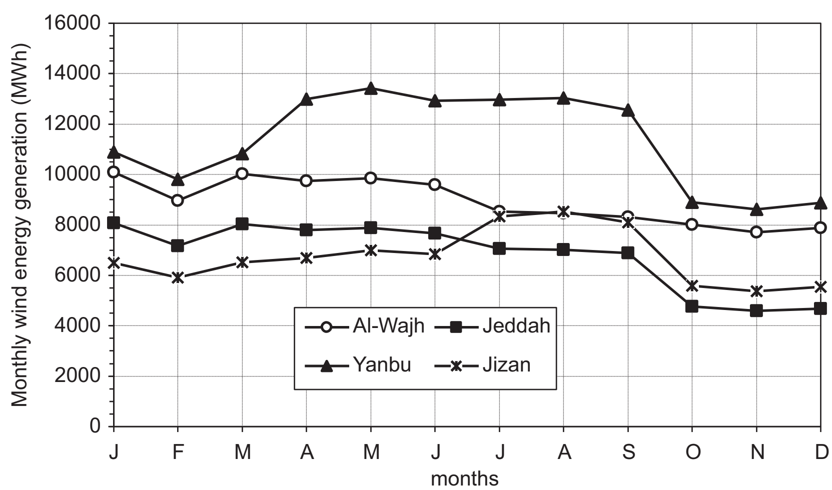

Fig. 7. Monthly energy generation from 75 MW wind farm (600 kW machines, hub-height 50 m) at different coastal locations of Saudi Arabia

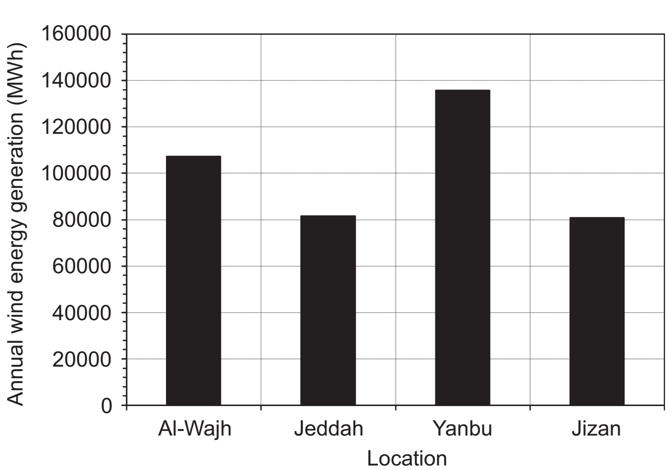

Fig. 8. Annual wind energy generation from 75 MW wind farm (600 kW wind machines, hub-height 50 m) for all selected coastal locations.

been found to be 107,196, 81,648, 135,822, and 80,896 MWh at Al-Wajh, Jeddah, Yanbu and Jizan respectively.

Diurnal power generated from 75 MW wind farm at Al-Wajh, Jeddah, Yanbu and Jizan sites is shown in Figs. 9–12. It is also evident from Figs. 9–12 that the power generated is higher during day time as compared to night time. This reflects that the diurnal pattern of the wind-generated power matches with the diurnal pattern of the electric energy demand (wind could provide a good complement to meet the peak loads).

4.2. Cost of wind based electricity ($/kWh)

The energy supply market is very competitive, led by utilities and fuel companies that meet nearly all our energy demands. Alternative energy sources like wind power provides new options and must be competitive with conventional energy sources, they also must be economical. A wind energy system requires a large initial capital investment.

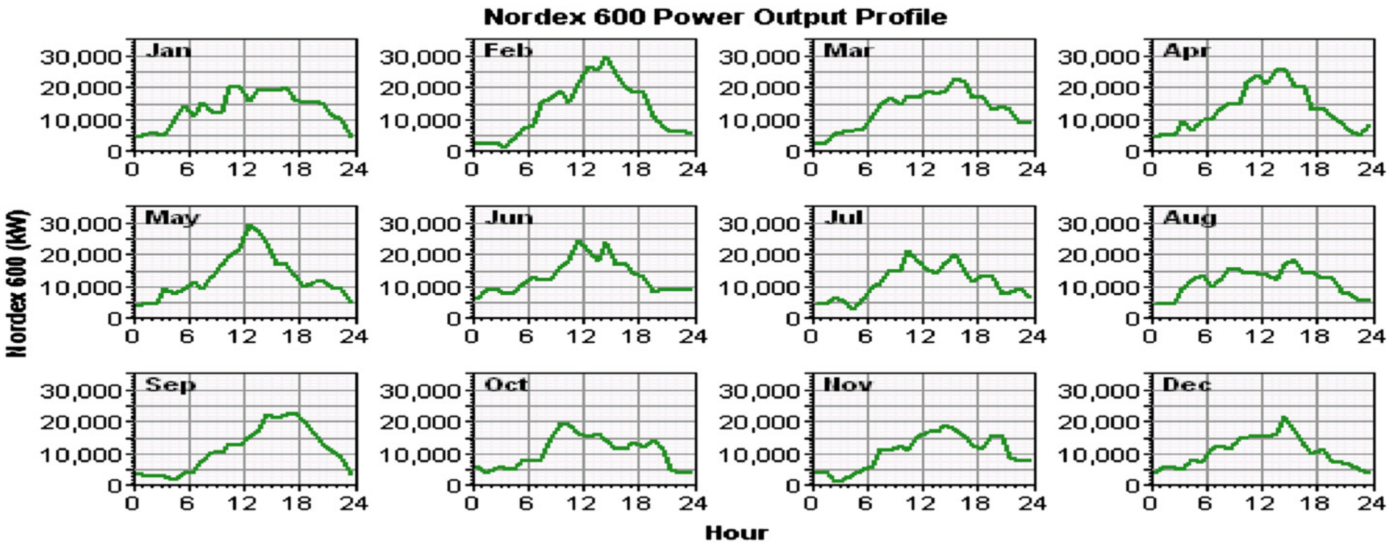

Fig. 9. Diurnal power generated from 75 MW wind farm at Al-Wajh.

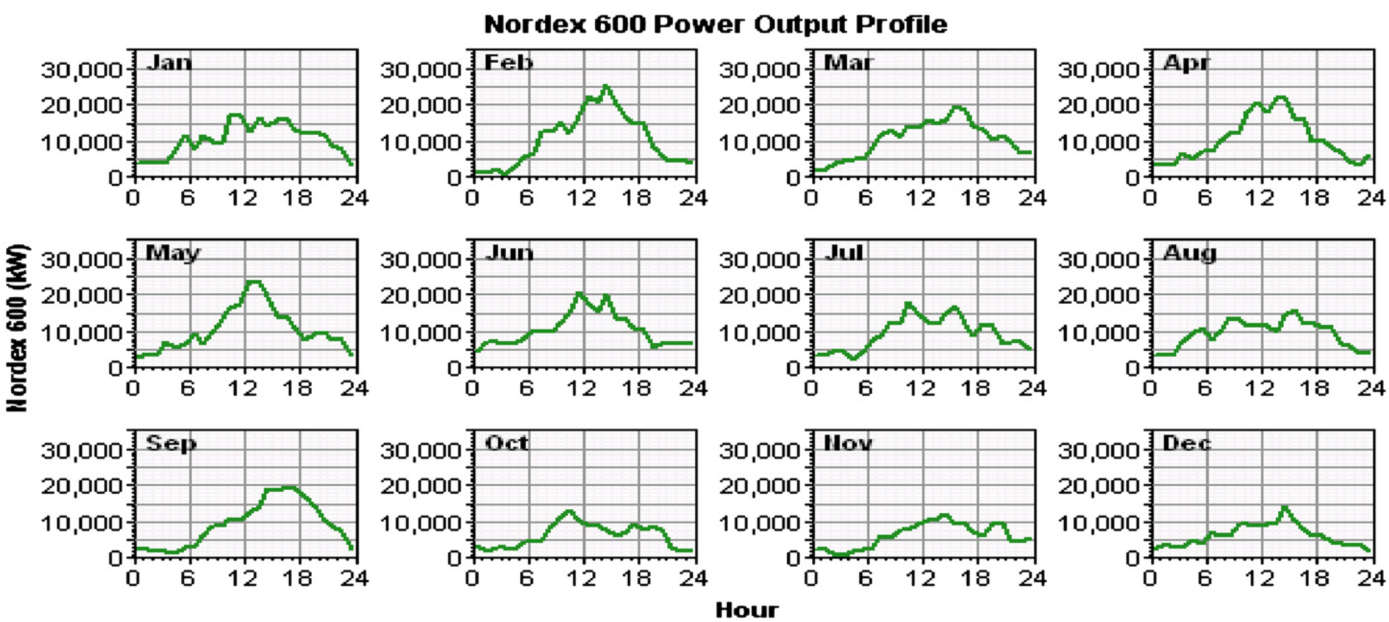

Fig. 10. Diurnal power generated from 75 MW wind farm at Jeddah.

The cost of energy (COE, US$/kWh) is one of the important issues in the wind energy industry. WECSs are generally designed to achieve high efficiency at low cost [13]. The cost of a wind system has two components: initial installation costs and operating (O & M) cost. The installation cost includes the purchase price of the complete system (including tower, wiring, utility interconnection or battery storage equipment, power conditioning unit, etc) plus delivery and installation charges, professional fees and sales tax. The total installation cost can be expressed as a function of the wind system's rated electrical capacity. A grid connected residential-scale system (1–10 kW) generally costs between $2400 and $3000 per installed kilowatt (i.e. $24,000–$30,000 for a 10 kW system). A medium-scale, commercial system (10–100 kW) is more cost-effective, costing $1500 and $2500 per kW. Large-scale systems of greater than 100 kW cost in the range of $1000–$2000 per kW. In general, cost rates decrease as machine capacity increases. The other cost component, i.e. operation & maintenance cost is incurred over the lifetime of the wind system. Operating costs include maintenance and service, insurance and any applicable taxes. A rule of thumb, estimate for annual operating expenses is about 3% of the initial system cost [40].

Cost of energy (COE) is computed by using the following equation**:**

Cost per kWh = (Annual cost)/(Annual energy output) …… (1)

Where Annual energy output is the projected annual energy output,

Annual cost = (Initial cost)/(Expected life) + Annual Operating Costs

The cost of generating energy (COE) per kWh from commercial 600 kW WECS (50 m hub-height) has been computed (for all the considered locations) by using equation (1) with a discount rate of 5% and is shown in Fig. 13. The study assumptions used in estimating COE are furnished in Table 2. Based on these study assumptions, the COE has been determined for all locations. The cost of wind-based electricity (COE, US$/kWh) by using 600 kW

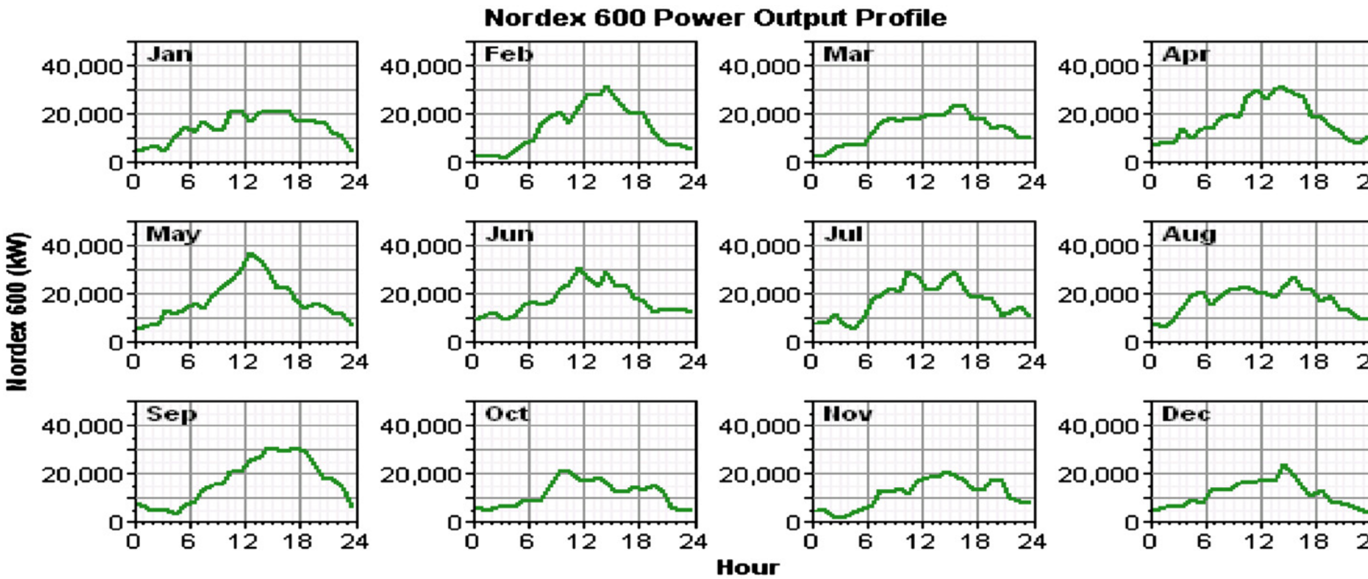

Fig. 11. Diurnal power generated from 75 MW wind farm at Yanbu.

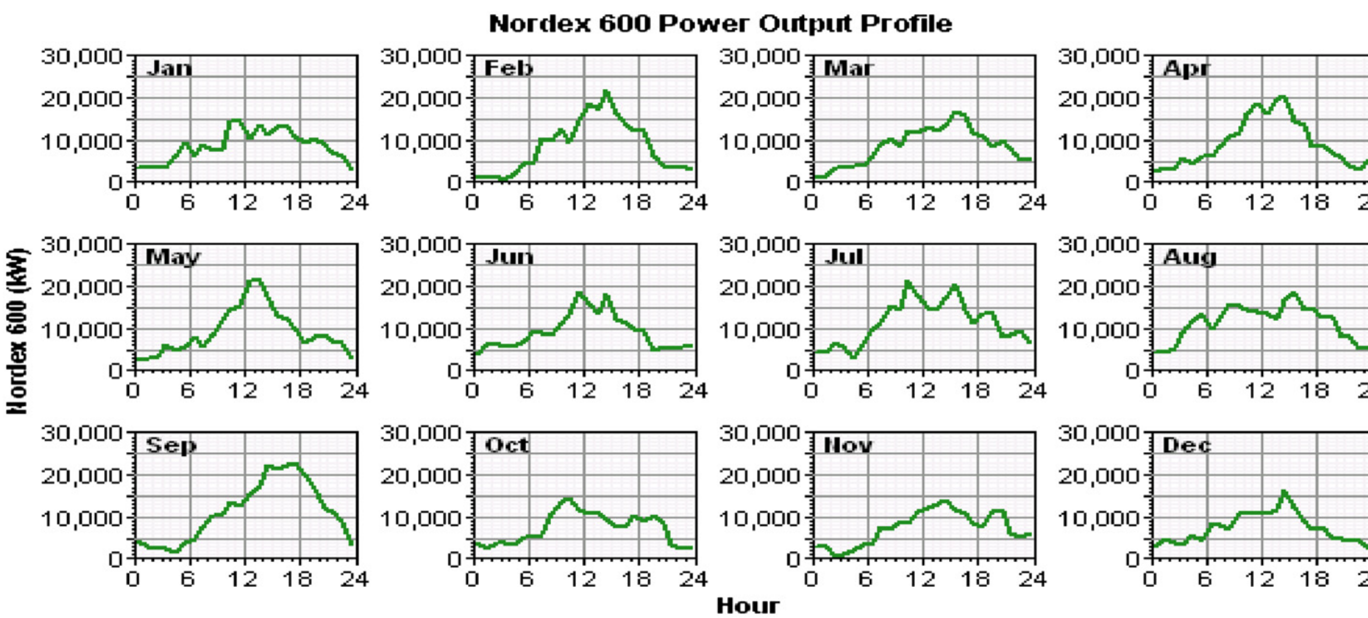

Fig. 12. Diurnal power generated from 75 MW wind farm at Jizan.

(50 m hub-height) commercial WECS has been found to be 0.0536, 0.0704, 0.0423, and 0.0711 US$/kWh for Al-Wajh, Jeddah, Yanbu and Jizan respectively. The topic of COEs of WECS of other countries is subject matter of studies by several researchers [10,11,13]. From investors point of view, the cost of electricity determines the economic attractiveness of a wind park. Therefore, in crisis, a trade-off need to be established between different options of power generation.

4.3. Capacity factor of wind-based power plants for different locations

The capacity factor is given as the ratio of the actual energy output to the theoretical maximum output, if the machine was running at its rated power during all the 8760 h of the year. The annual energy yield is understood as the total number of kilowatt-hours actually produced by a wind turbine installation or a wind farm in a year (at a given hub-height). The capacity factor is an important indicator in measuring the productivity of a wind turbine. Although capacity factors may theoretically vary from 0% to 100%, in practice they usually range from 20% to 70%. The capacity factors are calculated using the following equation [41]:

Capacity factor (%)=[Actual energy output/(Rated Capacity $\times$ 8760)] $\times$ 100

The capacity factor of wind-based power plants at different locations/regions of the Kingdom is presented in Fig. 14. The capacity factor has been found to vary from 12% to 21% for different coastal locations of the Kingdom (by using 600 kW WECS, 50 m hub-height).

The larger the capacity factor, the better the WECS. The capacity factor of Al-Wajh and Yanbu is higher as compared to other locations. The capacity factors of Al-Wajh and Yanbu are 16% and 21% respectively. This represents about 1402 and 1839 h

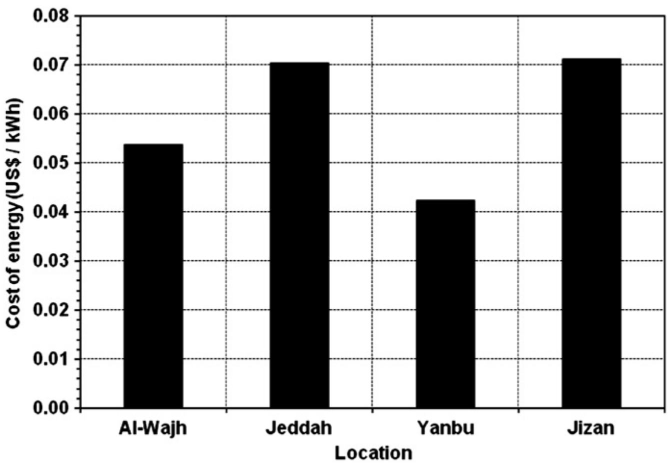

Fig. 13. Cost of Energy (US$/kWh) for different selected location (for 600 kW wind machine, 50 m hub-height).

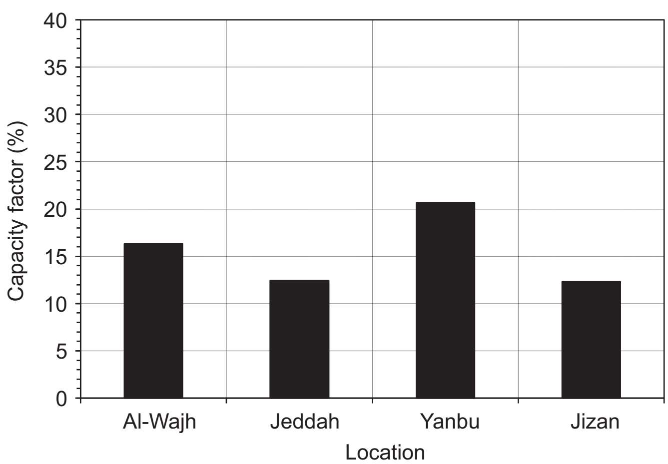

Fig. 14. Capacity factor of wind farms for different selected locations (for 600 kW wind machines, 50 m hub-height).

of full load operation. Discussions on capacitor factor of wind power plants in other Gulf countries are reported in literature [9,10,12].

5. Conclusions and recommendations

The present study has discussed in appreciable depth the economic feasibility of development of 75 MW wind power plants (wind farms) at four coastal locations of the Kingdom of Saudi Arabia. Specifically, attention has been focused on the monthly/seasonal variations of wind speed, frequency distribution profiles of wind speed, monthly and yearly amount of energy that can be generated from the proposed 75 MW wind farms (50 m hub-height), diurnal power, cost of energy (US$/kWh), capacity factor (%), etc. The cumulative frequency distribution indicates that the wind speeds are less than 3 m/s for 45%, 53%, 41%, and 52% of the time during the year at Al-Wajh, Jeddah, Yanbu and Jizan respectively. This implies that wind electric conversion systems (WECS) or wind farms (if installed in Saudi Arabia) will not produce energy for about 41–53% of the time during the year. The annual energy produced by 75 MW wind farms (50 m hub-height) has been found to be 107,196, 81,648, 135,822, and 80,896 MWh at Al-Wajh, Jeddah, Yanbu and Jizan respectively. The cost of wind-based electricity (COE, US$/kWh) by using 600 kW (50 m hub-height) commercial WECS has been found to be 0.0536, 0.0704, 0.0423, and 0.0711 US$/kWh for Al-Wajh, Jeddah, Yanbu and Jizan respectively. Attempt has been made to determine the capacity factor (CF) of wind-based power plants, the CF has been found to vary between 12% and 21% (Yanbu) for different locations. This indicates that Yanbu is relatively better/promising candidate for harvesting wind power as compared to other coastal locations. The results also aid in identifying economically/technically feasible site for development of wind farms. The present study forms a basis/road-map/benchmark/platform to identify feasible or potential coastal locations for wind farm development.

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